A study of planetary nebulae. Distances and physical properties.

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CHAPTER 6 SUMMARY

This investigation had two main purposes. The first was to determine individual distances of a number of planetary nebulae (PN) in order to considerably enlarge the sample of PN with accurate distances. The second purpose was to use these distances to investigate several properties of PN such as their intrinsic physical parameters, their evolution in the Hertzsprung-Russell diagram and to verify the validity of various statistical distance scales of PN.

In Chapter 2 a frequently used statistical method for the determination of PN distances, the "Shklovsky method", has been investigated. This study was based on high resolution radio observations of about 40 PN at the galactic centre (Chapter 2A) and of K 648 in the globular cluster M15 (Chapter 2B).

In Chapters 3 and 4 two methods to determine distances to PN have been described and applied. In Chapter 3 distances to 12 PN have been determined from relations of interstellar reddening as a function of distance along the lines of sight towards the PN. In Chapter 4 distances to 11 PN have been derived using 21 cm HI absorption measurements.

In Chapter 5 the distances derived in Chapters 3 and 4 and other accurate distances already published have been combined to a sample of 30 PN with "standard distances". This sample has been used to determine intrinsic parameters of the PN, to study their evolution and to investigate several statistical distance scales.

The main results and conclusions of the studies presented in Chapters 2 to 5 are summarized below.

1) Using high resolution 6 cm observations obtained with the VLA, accurate flux densities and angular sizes could be determined for about 40 PN at the galactic centre and for K 648 in M15. The ionized nebular masses derived vary from $\lesssim 0.008\ M_\odot$ to $\sim 0.6\ M_\odot$. These results show that the Shklovsky method for determining distances to PN will generally lead to unreliable distances.

2) Accurate Walraven VBLUW photometry of stars in small fields around 13 PN has been obtained. Using theoretical model atmospheres the effective temperature T_{eff} and surface gravity log g could be derived for program stars with $T_{eff} \gtrsim 7000$ K. Distances to these stars were determined using a calibration of absolute magnitude as a function of T_{eff} and log g. This calibration has been derived from theoretical evolutionary models. It could be shown that the calibration used leads to quite accurate

distances of the program stars; the systematic errors are probably smaller than ~ 10%. The scatter in the resulting reddening-distance relations along the lines of sight towards the PN could in all but two cases be explained by errors in the distances of individual program stars. This shows that the irregular distribution of dust across the sky is not necessarily the limiting factor in the application of the reddening-distance method, if stars within a few tenths of a degree from the PN are used.

The values for the interstellar extinction in the direction of the PN studied have been determined accurately. Several methods were used such as a comparison of the Hβ flux with the radio continuum flux density and the strength of the absorption feature at λ 2200 Å in the UV spectra of PN, obtained with the IUE satellite. Using infrared observations obtained by IRAS, it has been shown that internal reddening is generally negligible compared to the foreground reddening of PN.

The reddening-distance relations, combined with the reddenings of the PN, provided distances to 12 PN with accuracies ranging from ~ 10 to ~ 40%.

3) HI absorption measurements of 24 PN together with absorption measurements of background sources near the lines of sight towards the PN have been obtained using the Westerbork radio telescope. HI emission spectra in the directions to the PN have been obtained with the Dwingeloo radio telescope. Using the kinematic distance information derived from these measurements, combined with distance information from other sources, it was possible to determine distances to 11 PN with accuracies ranging from ~ 25 to ~ 40%.

4) The distances derived with the reddening-distance method and by means of the HI absorption measurements, combined with distances already published, a sample of 30 "standard distances" has been constructed. These distances are accurate within ~ 40%. At present this is the largest sample of accurate distances to PN that is available.

5) Using the sample of standard distances it was possible to give accurate positions of the PN in the Hertzsprung-Russell diagram. A comparison of these positions with theoretical evolutionary tracks shows that there are severe discrepancies between theory and observations. The observations show a considerable spread in central star luminosities while theoretical models predict a narrow range in luminosity. It is shown that the most plausible explanation for this discrepancy is that the evolutionary time scales predicted by theory are not correct. It is suggested that these time scales can be adjusted by using different theoretical values for M_{eN}, the remnant envelope mass of the central star at $T_{eff} = 3\ 10^4$ K. Adjustment of M_{eN} can be accomplished by a

revision of the value for the envelope mass immediately after envelope ejection, and/or by incorporating higher mass loss rates after the superwind phase than assumed in present theoretical models.

The observed positions of the PN in the Hertzsprung-Russell diagram imply that the mass distribution of central stars is less narrow than found earlier and is therefore in better agreement with the mass distribution of white dwarfs. This is also consistent with the observational fact that the local birthrates of PN and white dwarfs are comparable.

The theoretical prediction that high-mass progenitor stars produce high-luminosity PN with higher He and N abundances than average is confirmed by the present observations.

6) It is found that for the sample of PN with standard distances the ionized masses vary from $\sim 0.002\ M_\odot$ to $\gtrsim 0.5\ M_\odot$. This confirms the results of the study of the PN at the galactic centre.

7) The standard distances are used to verify the validity of various statistical distance scales. It is shown that individual distances derived from these scales are generally quite unreliable. This is due to the large spread in intrinsic parameters such as ionized nebular mass and central star luminosity. It is shown that a unique distance scale for all PN cannot be defined. Each of the published scales is in fact a mixture of several scales which represent PN that have originated from stars with different initial masses.